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# DISPLACEMENT DEWATERING TO MAINTAIN BULK

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## ABSTRACT

In conventional pressing operations, water removal is intimately linked to sheet densification. If water removal could be partially decoupled from densification, the papermaker could have more control over sheet properties. This has been the objective of an ongoing study of displacement dewatering, in which a pressurized air or steam phase is used to expel liquid water from paper while the paper is simultaneously under mechanical pressure. Displacement dewatering combines mild wet pressing with vapor-liquid drive to increase and maintain the hydraulic pressure gradient for water removal. Displacement dewatering differs from through-drying, in which a gas phase blows through the paper to evaporate water. In displacement dewatering, a true displacement process is desired in which a gas-liquid interface is maintained.

Recent experimental results with bench-scale equipment are reported. The data suggest that displacement dewatering can be a useful dewatering process for some grades of paper and for some specialty products. It has the potential to increase water removal without significantly increasing sheet densification. The greatest problem appears to be the long gas application times required. Typically, the displacement dewatering process requires over 50 ms for effective water removal, which may be impractical for many processes. Improved strategies are being explored to more fully tap the potential of a displacement dewatering process.

## INTRODUCTION

Thanks to innovations in the design of press felts and press equipment, water removal capabilities in the press section have progressed significantly in the last several decades, allowing ever higher dryness levels to be achieved. However, higher dryness is usually coupled with higher sheet density. While high density is correlated with increased strength, it is also correlated with lower opacity, bending stiffness, porosity, and liquid uptake, making high density undesirable for some grades. In such cases, the trade-off between bulk and dryness poses unwanted constraints on the papermaker.

Energy-efficient dewatering techniques which decouple density and dryness could be of significant benefit to the industry. One proposed means of achieving this objective is through displacement dewatering, in which a pressurized gas phase is used to drive liquid water out of a mechanically compressed sheet. In theory, the externally imposed gas pressure could supplement the normal hydraulic pressure gradient in a sheet that forms as the sheet is compressed. Because gas pressure would increase and extend the usual hydraulic pressure, driving more water out of the sheet, higher dryness levels could be achieved without further mechanical compression of the sheet. Dryness and density could thus be decoupled to a degree, potentially giving the papermaker added control over sheet properties and possibly a lower energy demand in the dryer section.

In this paper, displacement dewatering refers to a process in which a gas phase is used to drive out a liquid layer in a compressed sheet. If true displacement dewatering is achieved, relatively little vapor would be required to pass through the sheet—ideally only enough to uniformly displace the free water in the interconnected pores of a compressed sheet. This concept, at least in its idealized form, differs from through-drying or impingement drying, in which large volumes of heated air are used primarily to evaporate water in the sheet, although the process of through-drying also removes some water by entrainment. While the objective is to decouple density and dryness, displacement dewatering still requires substantial applied pressures to saturate the sheet and create an interconnected liquid layer which can be displaced by gas. In practice, the gas is likely to break through some pores in the sheet and remove water by entrainment and evaporative drying, but the objective is uniform displacement. Heated air or steam could be used, resulting in a process in which displacement of liquid water is accompanied by evaporative drying.

A displacement dewatering process might be of interest in grades such as linerboard, boxboard, and some printing papers and specialty products where the sheet is too heavy for through-drying or other techniques suitable for lightweight, highly porous paper, but where bulk is still desired. Piece goods such as paper plates may also benefit from displacement dewatering.

In the displacement process under consideration, a sheet would be subjected to moderate mechanical pressures to increase sheet saturation, probably in the range of 30-300 psi, while simultaneously being exposed to compressed gas. One possible implementation is shown in Figure 1. The apparatus envisioned here is like a suction roll operating in reverse, with multiple low-pressure long nip shoes to maintain the displacement process for a sufficient time.

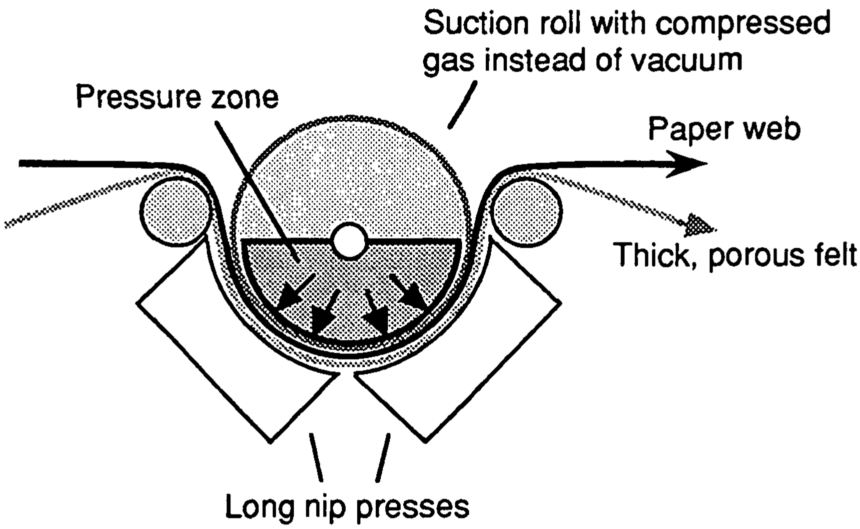


Figure 1. Possible implementation of the displacement dewatering concept.

This paper describes the recent results of an ongoing study on the potential of displacement dewatering, and attempts to evaluate the possible commercial importance of this technology.

# RELATED WORK

## Blow-Through/Through-Drying Concepts

### Entrainment and displacement

Several technologies exist to remove water from wet webs through physical entrainment or displacement when air blows through. For example, Holden (1) proposed several devices to dislodge and entrain water in a porous sheet by blowing air through the z-direction over a sufficiently long time (>50 ms). An example relevant to the present study is shown in Figure 2. In this apparatus, light mechanical pressure was to be applied to the sheet by felt tension as the sheet received air flow from a perforated roll.

Holden's concept was extended by Kawka and co-workers (2-9) over a number of years. Kawka used some of the devices as proposed by Holden, such as that in Figure 2, and invented others which also passed gas through a sheet under low mechanical pressures applied by porous belts, wires, or felts (2-4). Kawka's work focuses on blowing air through paper, especially absorbent papers and boards. In one study, for example, unheated air pressures from 0.01-0.08 MPa were used with exposure times of 0.1-1.0 s to dry absorbent papers (5). Solids content was raised from 10% to 30-40%, although a 28 gsm napkin tissue was dried from 18% to 87% solids in 0.5 seconds using air heated to 130°C.

In general, the blow-through process, with light mechanical compression, is severely limited in the dryness that can be achieved in short times. For example, with bag paper of 70 gsm, Kawka reports solids out of up to 43% are obtainable with 0.6 seconds exposure time of room-temperature air passing through the sheet (6). Initial solids content was 31%. In a thorough, recent study of through-drying with room-temperature air, Kawka reports that the time required to remove the free water in paper is about 5 seconds with air pressures on the order of 0.1 MPa (7).

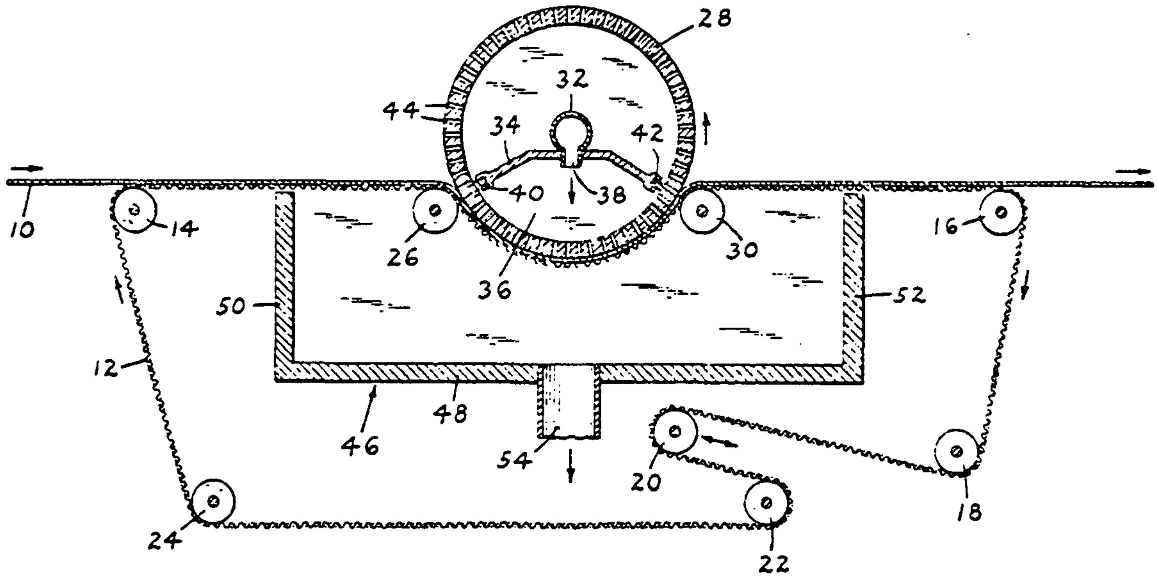


Figure 2. A blow-through dryer proposed by Holden (1).

The theory of through-drying is treated in (8). While Kawka claims that displacement of water from pores takes place in wet sheets with initial solids below 25%, more important seems to be the entrainment of water particles which occurs as air passes through the sheet with velocities on the order of 100 m/s (9). He states that the process works best at solids contents around 35%. All devices used by Kawka and Holden have the following characteristics:

- low mechanical compression (e.g., < 0.1 MPa) on the sheet
- long exposure times (0.05 - several seconds)
- modest applied gas pressures (typically < 0.2 MPa)
- air as the displacing medium, typically unheated
- low operating speeds (< 300 m/min).

The blowthrough concept has been aimed primarily at lightweight grades, such as towel and tissue, as well as bag papers. One article mentions application to heavyweight board, but no data are given (9).

**Thermal processes (evaporation)**

Evaporative through-drying with heated air is a well-developed technology in which the air is passed through a highly porous sheet under minimal compression (10-13). Because the hot air contacts water across a large surface area inside the sheet, evaporative heat transfer is very efficient. Displacement is not likely to occur, but some liquid may be removed by entrainment. Tissue and toweling are prime grades for through-drying, although various filter grades, roofing felts, wiper grades, and many wet-laid nonwovens can be used (12).

Both cylindrical and flat-bed through-dryers are used. One example of a cylindrical through-dryer is shown in Figure 3. A porous roll can be sufficiently strong to withstand high pressure differentials. Using a roll with a highly open honeycomb structure, Randall (14) reports pressures up to about 0.03 MPa or 5 psi, while a drilled suction role could support still higher pressures at the cost of less open area. With high differential pressures, sheet transfer may be impaired. Flat-bed through-dryers, as shown in Figure 4, pass the sheet between high and low gas pressure zones on a conveyor device. Sheet transfer is easy, but the process is limited to lower pressures.

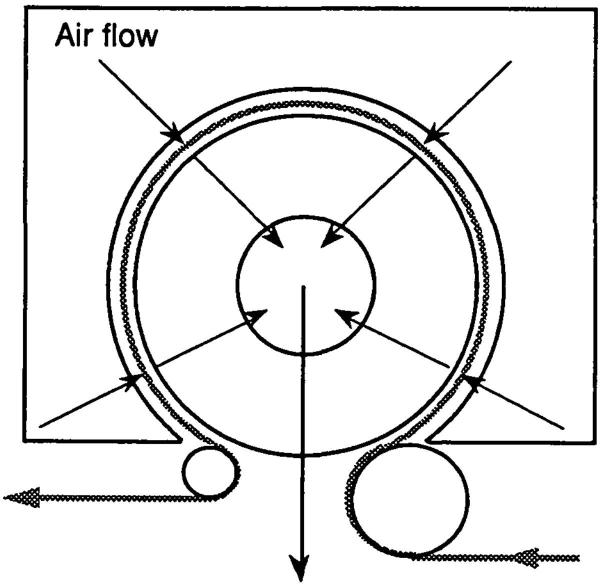


Figure 3. A cylindrical through-dryer.

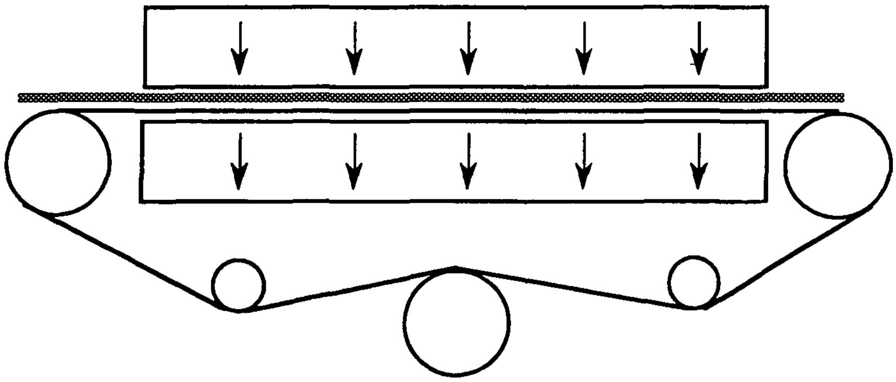

Figure 4. A flat-bed through-dryer.

High velocity gas impingement in tandem with through-drying has been investigated and patented by Burgess et al. at the Pulp and Paper Research Institute of Canada (15,16). In this "Papridryer" system, vacuum pressure inside a drilled suction roll pulls hot air through the sheet, decreasing boundary layer heat transfer resistance in impingement and causing internal heat transfer in the sheet.

**Other Dewatering Processes**

Impulse drying, a novel dewatering process under development at the Institute of Paper Science and Technology (IPST), may induce a displacement process which enhances liquid water removal from a sheet. In this process, a web and a felt pass through a nip in which one roll is heated to around 250°C (17,18). During the period of brief but intense heat transfer, with peak heat fluxes on the order of 4 $MW/m^2$, a high-pressure steam zone may form in the nip which can displace some liquid water or at least resist rewetting (19,20).

A related concept of gas-liquid displacement in dewatering was addressed in a patent awarded to Gottwald et al. in 1967 (21). Their proposed device was a heated drum at 120-250°C, wrapped with a wet web held in place by a porous belt under enough tension to cause at least 0.03 MPa (5 psi) of pressure on the web. They claim that vapor generated at the drum-web interface would drive liquid water into the porous belt, reducing the evaporative load on subsequent dryers. The proposed physics seem questionable, as a saturated liquid layer is not likely to exist under these conditions, but the possibility of *in situ* steam-liquid displacement clearly was envisioned.

Use of a high velocity gas nozzle to remove water by atomization was patented by Clemens and Morton (22). This method is related to some versions of through-drying in that entrainment of liquid water takes place, but Clemens and Morton use a small, high-pressure, high-velocity jet from a nozzle which is claimed to remove water from low-density webs at web speeds as great as 6,000 feet/min (30 m/s). Their objective was to remove water without decreasing bulk. The process is intended for very light grades such as tissue.

**The IPST Displacement Concept**

The displacement dewatering concept discussed here employs conditions well outside the realm of the through-drying processes discussed above. Specifically, the dewatering process under consideration:

- employs mechanical pressures great enough to liberate a substantial amount of water in the sheet, with conventional pressing pressures being possible;
- is intended to use brief intervals of time, less than 0.3 seconds and preferably under 100 ms to permit operation at practical speeds;
- seeks to raise solids levels of incoming sheets at 20-30% solids to beyond 40-50% to save drying energy as well as offer better control over bulk.

The current study actually began in 1985 with exploratory work done by Wahren, Ahrens, and Sprague at the Institute of Paper Chemistry in Appleton, Wisconsin (now IPST in Atlanta, Georgia). The work reported here is a continuation of the same project, resumed in 1987, which has suffered a number of major delays and interruptions over the past several years. Early results were reported by Sprague (23). Room temperature air only was used in a series of brief experiments using lightweight sheets with several displacement devices. The equipment used posed a number of problems. In particular, drying was nonuniform due to improper air flow distribution. Large drilled holes in the platens led to nonuniform mechanical pressures. Air leakage around the edge of the sheet also appears to have been a problem. New equipment for this study was designed to overcome these problems, as described below.

Sample results from the early portion of this project (23) are shown in Figure 5. Here a sheet was subjected to mechanical compression between plates with a number of holes. After 60 ms of compression, a valve released a burst of compressed air which continued for another 60 ms, with gas pressure maintained past the end of the pressing event. The low gain in solids when no air was used must reflect the inefficiency of wet pressing between two drilled platens; conventional wet pressing under similar press conditions would have undoubtedly given much better dryness levels.

In examining trends in density and dryness, Sprague found evidence that gas displacement can allow significant water removal to be achieved without the normal degree of densification. This possibility will be examined in more detail in this paper.

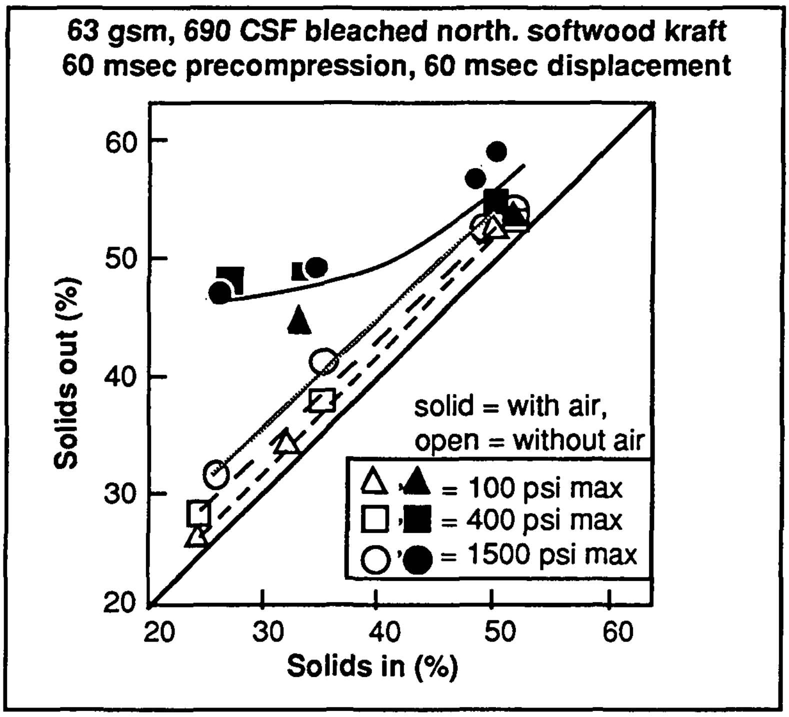


Figure 5. Dewatering results obtained with early displacement dewatering equipment at IPST (23).

## THEORY OF DISPLACEMENT DEWATERING

### Limits to Water Removal: The State of Water in the Sheet

The interaction of gas with water in a sheet of paper depends on a number of factors. Most critical, perhaps, is the state of the water with respect to the porous structure of the paper. Gas displacement will not remove water that is chemically or physically bound to the fibers or water that is trapped in dead-end or isolated pores. The potential of displacement dewatering is limited by the amount of water available for flow at a given compression.

A variety of studies have been conducted to understand where the water is in the sheet and how much might be available for removal. Lindström (24) provides an excellent review of this topic. Useful information can be obtained from water retention values, solute exclusion measurements (25,26), and from values of specific volume (a better term would be "associated volume") of fibers from permeability measurements (27,28). Based on such information, a perfectly efficient displacement dewatering method without high mechanical compression is unlikely to exceed dryness levels of 50-60% in typical papers. As with conventional wet pressing, much of the water to be removed may need to be pressed out of the cell wall (29). The potential advantage of displacement dewatering is that more of the free water can be removed, so a given solids level may be obtained at lower pressures than required in wet pressing.

### The Physics of Gas-Liquid Displacement

Gas-liquid displacement flows in porous media pose a challenging problem in analysis. The problem involves the unsteady flow of two immiscible fluids through a nonhomogeneous solid matrix, with capillary and viscous forces that are linked to the porous structure, to the local values of saturation, and to the history of the domain (i.e., hysteresis effects can be significant). An accurate prediction of gas-liquid displacement in this case becomes computationally unfeasible and would still require measured parameters that are generally unavailable for paper. However, simple limiting estimates of performance are possible if one assumes that a sharp interface separates the gas and liquid phases. This commonly employed assumption may be useful in some simple cases when high displacement velocities occur (30), although it is expected to be only a crude tool for the problem at hand.

**Speed of displacement**

One simple but key issue in displacement dewatering is the length of time the gas pressure must be applied. The sharp-interface assumption may be applied to give a *lower* limit. Consider the one-dimensional motion of a sharp, stable gas-liquid interface driven by constant gas pressure through a uniform porous medium of thickness $L$ and permeability $K$. The gas liquid interface is at position $x$, with $x=0$ at the flow exiting side of the sheet. The pressure drop across the sheet is $\Delta P$. Neglecting inertial effects and the viscosity of the gas phase, we can apply Darcy's law to determine the interface velocity:

$$V = -\frac{dx}{dt} = \frac{K}{\varepsilon\mu}\frac{\Delta P}{x} \tag{1}$$

where $V$ is the interface velocity, $\varepsilon$ is the sheet porosity, and $\mu$ is the liquid viscosity. The time required for the interface to move across the entire porous medium beginning at the upper surface ($x=L$) is given by:

$$\int_L^0 -x\,dx = \int_0^t \frac{K\Delta P}{\varepsilon\mu}\,dt' \tag{2}$$

resulting in

$$t = \frac{\varepsilon\mu L^2}{2K\Delta P} \tag{3}$$

where $t$ is the required time. Let us apply typical conditions for a linerboard sheet. The viscosity of the warm water could be 0.0007 Pa-s, the compressed sheet might be 0.2 mm thick with a permeability of $4.0\times10^{-16}$ $m^2$ and a porosity of 0.6. If gas is applied at a pressure of 0.5 MPa (73 psi), Equation (3) predicts that the gas-liquid interface will move across the sheet in 42 ms. A thicker or less permeable sheet will require more time. In reality, the displacement process will not be so efficient. The gas-liquid interface will not move smoothly but will break up because of inherent instabilities, which are discussed next.

**Interface stability**

When a liquid is displaced in a porous medium by another immiscible fluid of lower viscosity, the interface between the phases is frequently unstable. This can be shown by simple stability analysis based on the sharp-interface assumption (31). Any small perturbation on the initially smooth interface will accelerate because of the lower pressure drop in the more mobile fluid, creating "viscous fingers" that penetrate into the phase being displaced, as shown in Figure 6 (32). For secondary oil recovery, this means that displacement of oil by water or gas will be inherently inefficient, since large portions of the oil may be bypassed by fingers that break through to the production well. In the paper industry, this means that a gas phase will tend to simply blow through certain paths in the paper, leaving much of the water behind. Based on the work of Lenormand et al. (33), who numerically examined displacement processes for a wide variety of conditions, the conditions typical to air-water displacement in paper clearly fall in a regime where significant viscous fingering is likely.

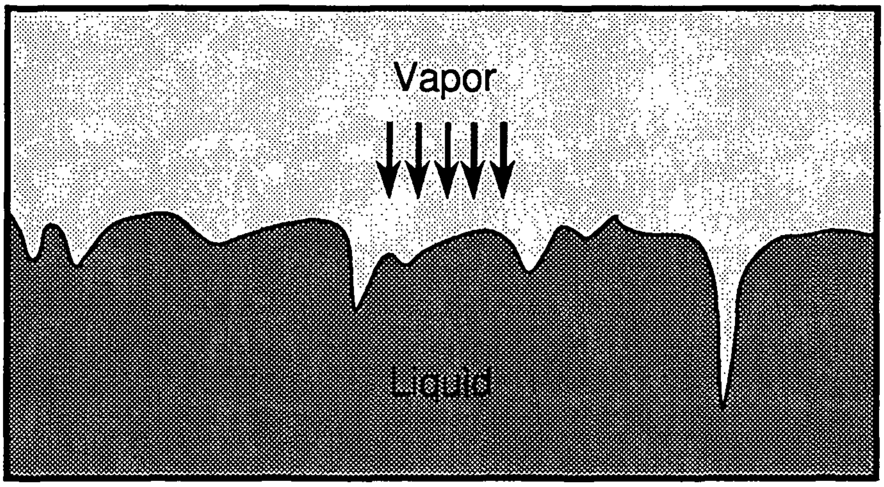


Figure 6. Viscous fingering in a porous medium as a gas displaces a liquid.

A number of factors have been shown to enhance stability. For example, if the viscosity of the displacing phase can be "artificially" increased, interface stability can be achieved. This artificial increase in viscosity can be achieved by using foams, which are mostly low-viscosity air but behave like a fluid with a very high viscosity due to the structure of the foam. In secondary or tertiary oil recovery, for example, foams have been used to increase the stability of displacement (34). In the paper industry, Skelton (35) has reported that application of foam to paper increases water removal by suction. Skelton writes that the reasons for this effect are unknown. The analogy to oil recovery, however, would appear to provide at least part of the explanation. The stability of the displacement process in suction is increased, and water removal becomes more efficient. Experimental work with stabilizing foams is planned for the current study, but has not yet been conducted.

Anisotropic permeability in paper can also enhance displacement stability. If the lateral permeability is greater than the normal permeability, a viscous finger could tend to spread out in the plane of the paper, thus creating a more uniform surface. Measurements of the full permeability tensor have been conducted in conjunction with the present study (36,37). The results to date indicate that the ratio of in-plane to transverse permeability is greater than unity, with an observed range of about 2-10. Paper made from TMP pulp had the greatest anisotropy ratios observed, near 10, while kraft pulps gave values consistently near 2 (37). Papers with higher lateral permeabilities may yield improved interface stability in displacement dewatering.

Heat transfer can also play a role in decreasing instabilities. If transient heat transfer from the vapor to the liquid is occurring, the interface becomes more stable (38). As a hot viscous finger penetrates into cooler liquid, the gas begins to cool and contract, thus decreasing the growth rate of the viscous finger.

When steam displaces water, the condensation of steam can significantly improve the stability of the vapor/liquid interface (38). For instance, as steam breaks through and contacts cooler liquid, it will condense. The viscous fingers become "self-sealing" to some extent, making the interface more stable. The combined effects of heat transfer and condensation are believed to make superheated steam a good candidate for displacement dewatering.

## EXPERIMENTAL APPROACH

### Equipment

An experimental displacement device (Figure 7) was constructed for this study. The displacement device consists of two heads installed in an MTS hydraulic press (Figure 8). The hydraulic ram drives the upper head and can control the motion and applied mechanical pressure to simulate pressing conditions. The upper head consists of a hollow chamber above a drilled bronze plate. The plate can apply mechanical pressure to paper and, at the same time, allow gas pressure to be applied. High-pressure gas is released from a pressure vessel into the upper chamber by a rapid solenoid valve. The extended, tapered sides of the upper head fit over the lower head and form a seal with an O-ring that encircles the lower head. The lower head is also a hollow chamber with a drilled bronze plate on top to allow gas to pass from the upper

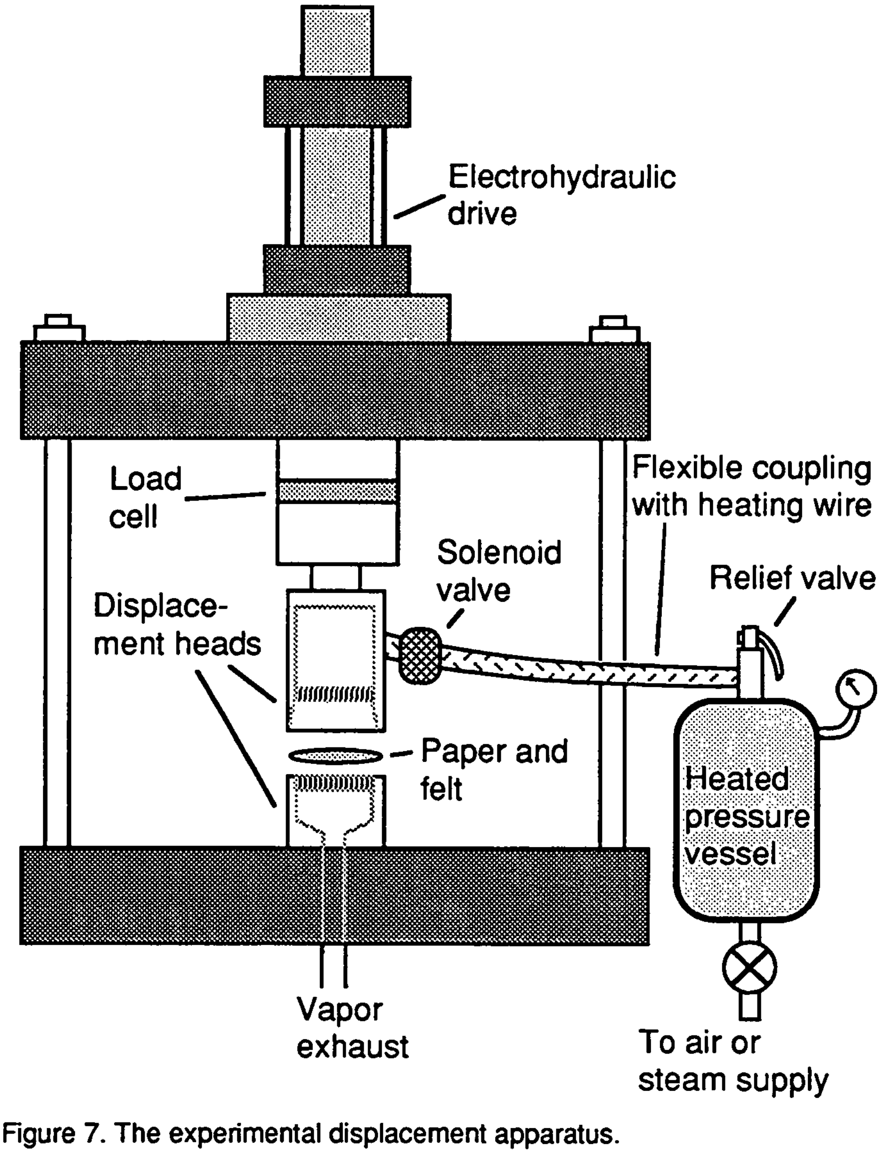


Figure 7. The experimental displacement apparatus.

into the lower head, and from thence into the atmosphere through a hole in the lower frame of the MTS system. The gas pressure in the upper head can be released by gas passing through the sheet and into the lower head, by escaping at the end of a press event when the O-ring seal is broken, or by passing through an opening in the side of the upper head.

The bronze plates are drilled with 0.09-in (0.0023 m) holes, with a center-to-center distance of 0.125 in (0.0032 m). The open surface area is 47%. The plates are sufficiently thick (1 in or 0.0254 m) to prevent significant bowing during compression. Carbon paper imprints between the platens were used to check head alignment in order to get a uniform applied pressure.

For displacement dewatering of paper, a 3-in (0.076 m) handsheet disk is

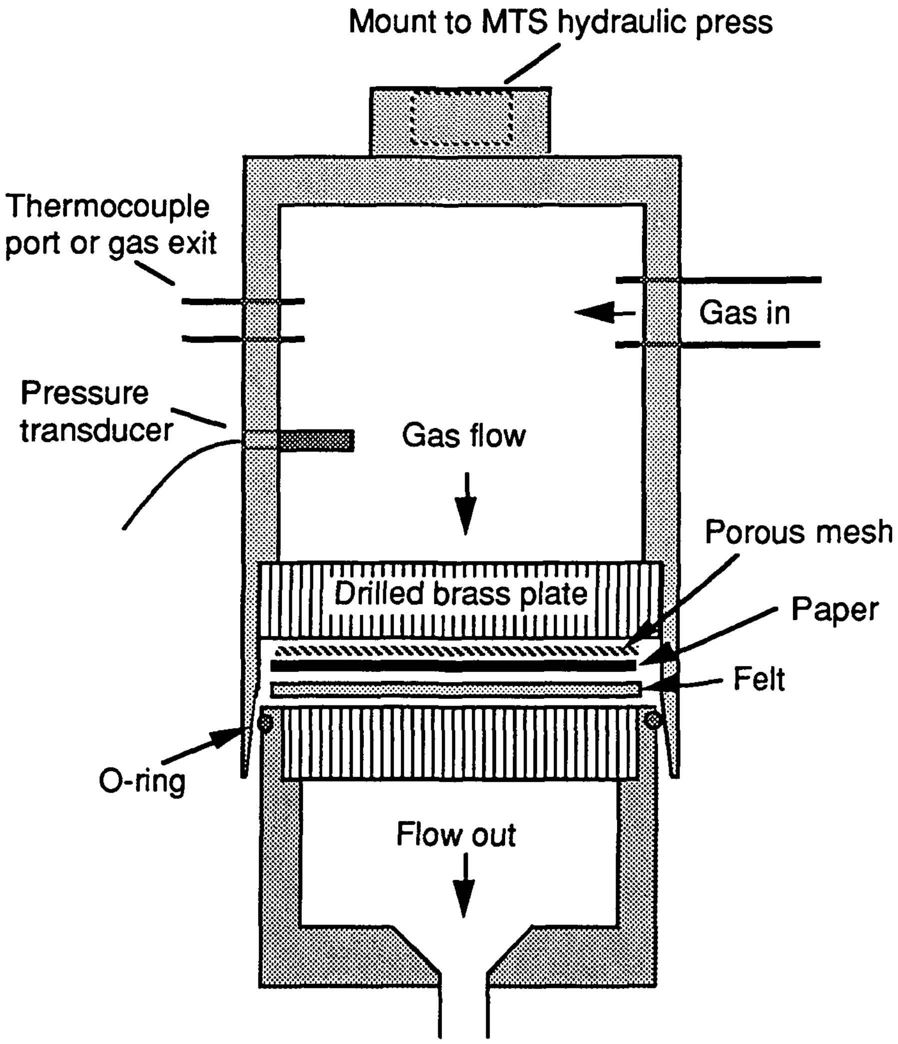


Figure 8. Detail of the displacement heads.

placed on a 3-in (0.076 m) felt. A fine, stiff disk of either a plastic forming fabric or copper mesh is placed on top of the paper to distribute the gas pressure uniformly over the paper. Tests have indicated that the gas pressure is applied evenly to the paper in the tests of this study. (A felt can also be used on top of the paper, and has proven successful in the most recent tests.) The fabric-paper-felt stack is placed on the lower drilled plate. An electronic switch then drives the upper head downward to apply a controlled pressure pulse typically lasting for 20-100 ms. As the mechanical pressure pulse begins, a relay switch opens the solenoid valve for a specified time and the pressurized gas then fills the upper chamber and begins to assist the dewatering of the paper. Gas pressures of 0.14-0.75 MPa (20-110 psi) have been used.

Unfortunately, the fastest solenoid valve which could be purchased still had a lag time of about 20 ms before the valve became fully open. Once the valve is open, the chamber reaches full pressure in about 5 milliseconds. A control system was thus devised that could trigger the solenoid valve within a range of over 100 ms before sheet compression begins to over 100 ms after compression ends. Generally, the solenoid was fired 10-20 ms before the beginning of the mechanical pressure pulse, providing a gas pulse to the sheet that began only after substantial compression had occurred.

The new displacement heads overcame the problem of nonuniform gas pressure by providing a large chamber above the sheet to allow the applied gas pressure to become spatially uniform during displacement. The uniform distribution of holes, combined with a porous mesh or felt to distribute the gas, also improved uniformity of gas application. An O-ring assembly prevented gas leakage from the upper chamber during displacement.

**"Unconfined" Displacement Dewatering**

The greatest difficulty with the new equipment, which also appears to have been a problem with earlier equipment used for this project, was controlling the duration of the applied gas pressure. We wished to release the gas pressure before the expansion phase of the press event began; this would keep the gas application time low and prevent significant blowing as the sheet decompresses and becomes more permeable. (Blow-through should not harm the sheet and may slightly increase the dryness by water entrainment and evaporative drying, but we wished to avoid significant air flows through the sheet.) Controlling the gas pressure proved problematic, however. We attempted to use a second fast-acting solenoid valve on the upper head to release the gas at a specified time. Unfortunately, even the best solenoids that we could locate did not perform as required. Solenoid valves require upstream pressure or flow to become properly seated; the burst of pressure as the first solenoid opened blew open the second solenoid before it could seat, releasing the pressure.

The first set of experiments was thus run with only one solenoid valve. The port which had served as the exit port to the second solenoid valve was sealed, and the applied gas remained pressurized until it either passed through the sheet or was released as the two displacement heads separated. As a result, the vapor pressure duration in the first set of experiments was undesirably long, ranging from 100 to 350 ms, and exceeded the duration of the mechanical pressure pulse. Since the gas pulse was not confined within the time of the mechanical pressure, these runs are termed "*unconfined*" displacement dewatering. Figure 9 shows pressure pulses during a typical unconfined run.

The long gas pulse in the unconfined runs allowed us to test the upper limits of the displacement process; if the displacement dewatering process cannot remove water at these conditions, there should be little reason to explore shorter durations.

**"Confined" Displacement Dewatering**

Following the somewhat favorable results of the first series, a second series of experiments was launched in which the duration of vapor displacement was shortened by leaving an opening in the gas exit/thermocouple port of the upper head. The open time of the inlet solenoid was also shortened as much as possible (too short a signal would lead to closing before the solenoid was fully open). With this arrangement, a series of tests with more desirable gas pulses could be achieved. Figure 10 shows the typical gas and mechanical pressure pulses for such a run. Since most or all of the gas pulse is confined within the mechanical pressure pulse, these runs are termed "confined" displacement dewatering.

**Run Procedures and Conditions**

Displacement dewatering and wet pressing runs were made in a variety of handsheets, primarily linerboard grades. The two main linerboard furnishes were a Northwestern softwood unbleached kraft (NWSK) and a Southern softwood unbleached kraft (SSK). Both furnishes had freeness levels of about 700 CSF. Some runs were made in handsheets from an unbleached thermomechanical pulp (TMP). The TMP had a freeness of about 100 CSF. Saturated 240 gsm commercial blotter paper was also used as an example of a heavy but highly permeable material. Recent results for a hardwood furnish, red oak unbleached kraft, will also be reported.

In each run, a wet sheet was weighed, then placed between a dry felt and the fine plastic or copper mesh, and the assembly was set on the drilled bronze plate of the lower displacement head. The MTS control system was activated, which would cause the pressing and displacement event to occur. As the

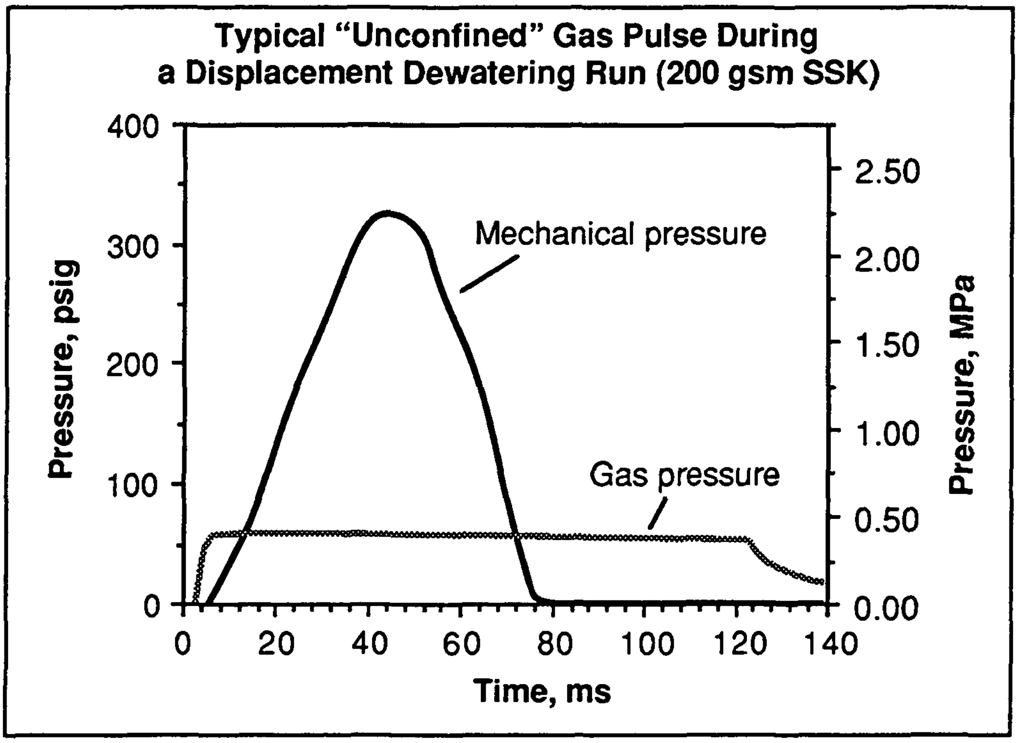


Figure 9. Applied gas and mechanical pressure pulses during a typical "unconfined" run. The gas pulse is not confined within the mechanical pressure pulse.

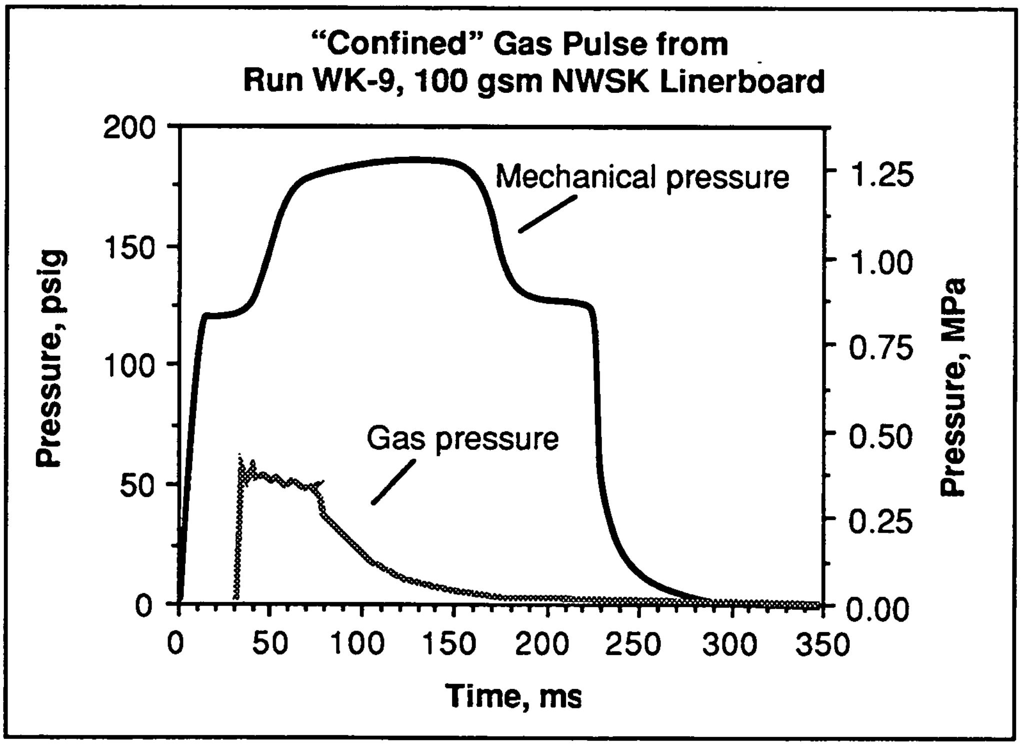


Figure 10. Applied gas and mechanical pressure pulses during a typical "confined" displacement dewatering run.

upper head retracted, the sheet was removed and weighed again. The sheet was then dried at about 100°C under mild constraint, and its thickness was measured at 4-10 random sheet locations to obtain an average. From this information, the solids in, solids out, and sheet density could be determined.

Displacement was done with both room temperature air and superheated steam. When steam was used, the pressure vessel and the flexible coupling to the upper displacement head were heated and insulated. The pressure vessel was heated with a band heater near the centerline, and temperatures measured there were typically 315-330°C. The heated flexible coupling to the solenoid valve was at about 175°C. The temperature inside the upper head just prior to displacement was 120-150°C, achieved by passing some pressurized steam through the head while compressing a disk of blotter paper on a felt. This head temperature was usually sufficient to prevent significant condensation in the head during a displacement event. Without this preheating of the head, condensate drops would often be found on the sheet after displacement.

The use of steam posed a number of problems. While condensation was prevented by heating the displacement head, the MTS system also warmed up. This often played havoc with the dynamic response of the system. The solenoid valve, rated for high temperatures, also tended to behave erratically with steam, frequently misfiring. A number of good runs were possible with steam, however.

The peak mechanical pressures in the displacement runs ranged from 180 to 400 psi (1.2-2.8 MPa), well below what is typically used in wet pressing. Nip residence times were large, however, with a range of about 70-300 ms. The lower limit is due both to control problems encountered in the MTS at low mechanical pressures and the dynamic limits in the gas application system.

The applied gas and mechanical pressure pulses were measured with a load cell and pressure transducer, respectively, and monitored with an oscilloscope. Digital readings of peak mechanical pressure and total pressing impulse were available.

### Wet Pressing Variants: Normal, Low Pressure, and Open Surface

To compare the densification of displacement dewatering with the densification of conventional pressing operations, we wished to press a number of sheets without any gas being applied. If displacement dewatering is done in the normal manner, but with gas at zero or very low pressure, the pressing efficiency is low. In such a pressing event, termed "open-surface wet pressing," the sheet is pressed by an open wire surface backed with an open drilled platen. (In Figure 5, for example, the data labeled "without air" represent open surface wet pressing.) Without significant gas pressure being applied, water may pool above the sheet and cause rewetting or sufficient hydraulic pressure for dewatering may not be generated. The low dryness levels achieved in this manner are an artifact of the experimental setup, and would be different if another gas delivery and distribution system were used, such as a porous platen composed of sintered metal without a layer of wire or fabric on the paper. Comparison of displacement dewatering to open-surface wet pressing is an inappropriate means of evaluating process performance.

To create a true wet pressing effect, the pressing surface of the sheet must be solid. By replacing the wire mesh with a rigid disk of acrylic plastic, wet pressing could be simulated in the displacement apparatus. Gas was not applied, of course, during such runs. During a series of displacement dewatering runs, occasional wet pressing results would be obtained using this method. The wet pressed sheets were thus subject to essentially the same mechanical pressure pulse as was used in the displacement dewatering tests of that particular run. Because the peak mechanical pressures were lower in these runs than is typically used in commercial wet pressing, this method of wet pressing is termed "low-pressure wet pressing." In the industrial practice of wet pressing, it is commonly noted that wet pressing density-dryness data tend to fall on the same curve, regardless of the details of the wet press operation. Therefore, during most of this study, it was simply assumed that the density-dryness data for a given sheet type obtained with low-pressure wet pressing would fall on the same curve as similar data sets obtained under different wet pressing conditions. This assumption was finally tested by obtaining "normal wet pressing" data.

"Normal wet pressing" in this study refers to wet pressing data obtained by pressing paper on a felt between solid platens using peak mechanical pressures from about 2-8 MPa and nip residence times of 20-50 ms. The applied mechanical pressures are higher and the nip residence times much lower in "normal wet pressing" than those used in the low-pressure wet pressing tests and are closer to the conditions used in commercial operations.

## RESULTS

### Water Removal and Densification

#### Unconfined displacement

The unconfined tests were run to check the upper limits of displacement dewatering. Being "unconfined," the gas exposure times were longer than the nip residence times, with total gas exposures on the order of 350 ms. Peak mechanical pressures were about 2.3 MPa. The results from this series gave positive indications that displacement dewatering could effectively remove water, and did not serve to disprove the concept. To further test the concept, it was necessary to run tests under the more critical confined conditions. Since the confined displacement results provide the most useful data for evaluating the proposed process, they will be emphasized in this paper.

One key set of data from the unconfined series with steam is given in Figure 11, where density-dryness relationships for three batches of 100 gsm handsheets are examined. Two batches of sheets were made from a Southern softwood unbleached kraft (SSK) furnish, and the other was from unbleached TMP. Most runs employed an 80 ms nip residence time, although in SSK batch 1, times up to 200 ms were used. Steam exposure times were on the order of 100-150 ms longer than the nip residence time. The enclosed shaded area contains the low-pressure wet pressing results (same mechanical pressure pulses as the displacement runs, with a solid surface in contact with the upper sheet surface), and the other data points give the steam displacement results.

The two linerboard batches give consistent results, indicating that lower densities are achieved than is possible with low-pressure wet pressing, and also indicating that high dryness levels can be achieved. Even more encouraging are the TMP steam results, where the density-dryness curve is flat. This suggests that high solids levels can be achieved with no significant losses in bulk. However, given the long exposure times of unconfined displacement, these results were probably achieved largely by thermally drying the sheet with steam rather than by displacing the liquid water. An energy balance has not been done, but this particular process is not likely to save energy costs. To more realistically explore the potential of displacement dewatering, we must consider results with confined displacement, where shorter gas exposure times are used and less gas is wasted by blowing through the sheet after the end of the nip.

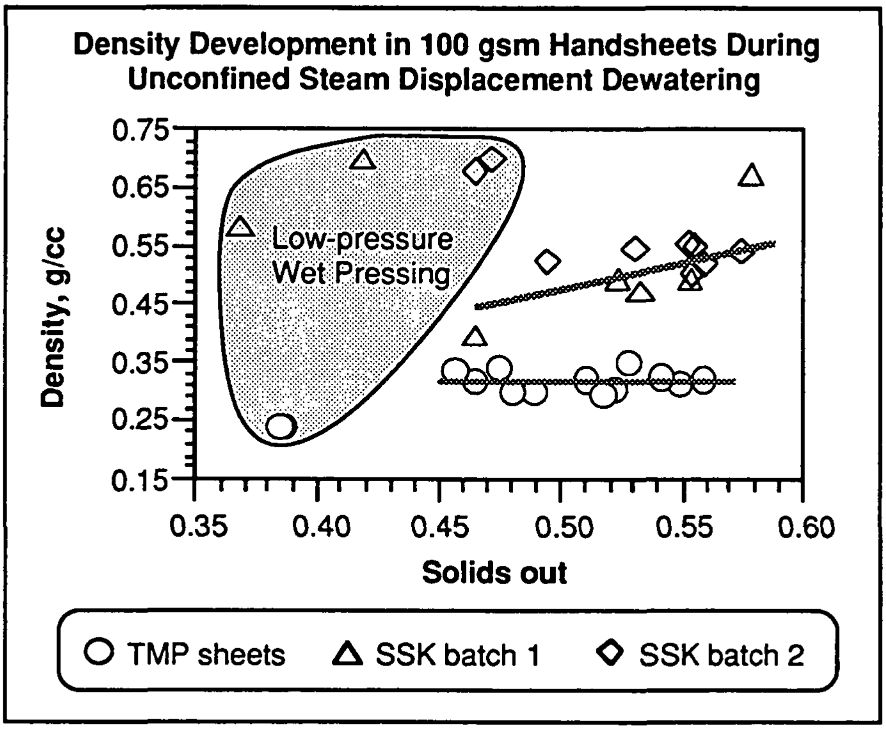


Figure 11. Density-dryness relationship for unconfined displacement dewatering with superheated steam.

**Low pressure, confined displacement**

In the confined displacement runs, the equipment and the MTS/solenoid valve dynamics were adjusted to ensure that most or all of the gas pressure was contained within the duration of the mechanical pressure pulse (see the discussion in the experimental section above). Low mechanical pressures were used, ranging from 1.2-2.1 MPa peak.

Saturated blotter paper was examined first in the confined displacement series. The data for air displacement in blotter paper are shown in Figure 12. Displacement dewatering yields higher solids levels than low-pressure wet pressing at the same press conditions, but low-pressure wet pressing at a moderately higher pressure (2.34 MPa or 340 psi peak) produces about the same dryness that was achieved with 0.55 MPa (80 psi) of air. Density effects were not considered in the blotter paper, which had already been dried prior to being saturated for this experiment (it was felt that the results would not be of any real value).

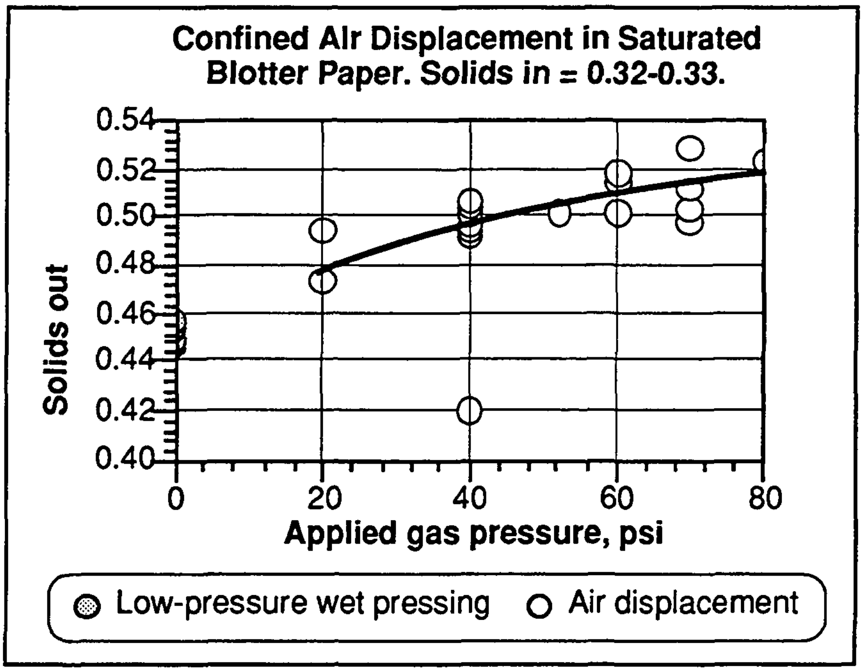


Figure 12. Air displacement results in saturated blotter paper.

More meaningful runs were then done with freshly made linerboard handsheets in order to examine the issue of bulk control with confined displacement dewatering. In particular, it was desired to not only compare displacement dewatering with low-pressure wet pressing under similar press conditions, but also to compare the results with normal wet pressing (done under conditions more closely related to commercial pressing, as described above).

The linerboard handsheets were made from the Northwestern softwood unbleached kraft (NWSK) furnish. First, normal wet pressing data were obtained. A variety of nip residence times and peak pressures were used to obtain a range of dryness values. Peak pressures up to 8 MPa were achieved, with residence times on the order of 20-60 ms. This was done for 100 and 150 gsm NWSK sheets.

Air displacement was then examined in 150 gsm sheets of this furnish. Nip residence times ranged from 120-140 ms, with peak pressures of about 2.3 MPa. Peak gas pressures lasted for 60 ms and total gas exposure time (gas over 10 psi or 0.07 MPa) was 120 ms. The water removal results are shown in Figure 13, and the density-dryness relationships for both displacement dewatering and normal wet pressing are shown in Figure 14.

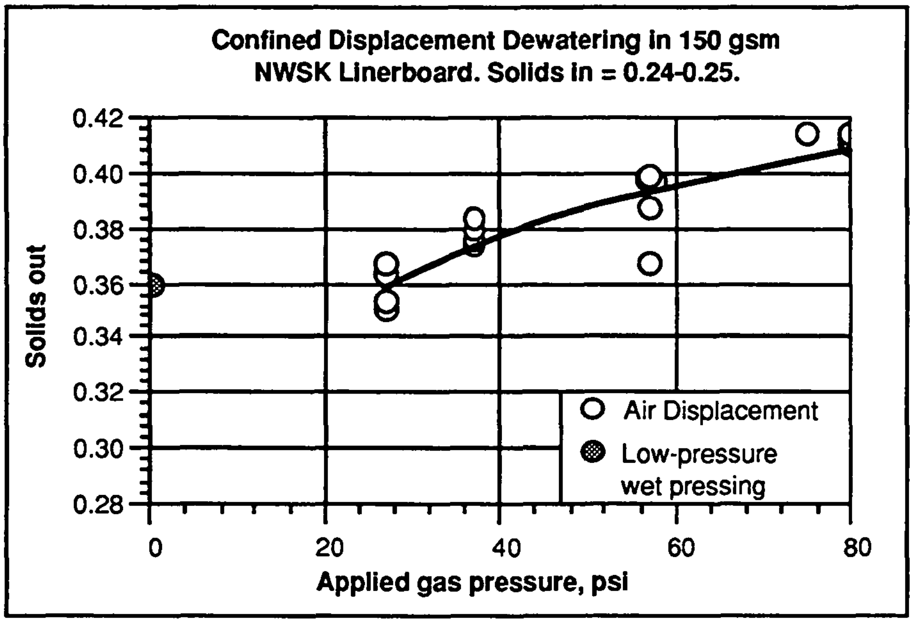


Figure 13. Confined air displacement in 150 gsm NWSK sheets.

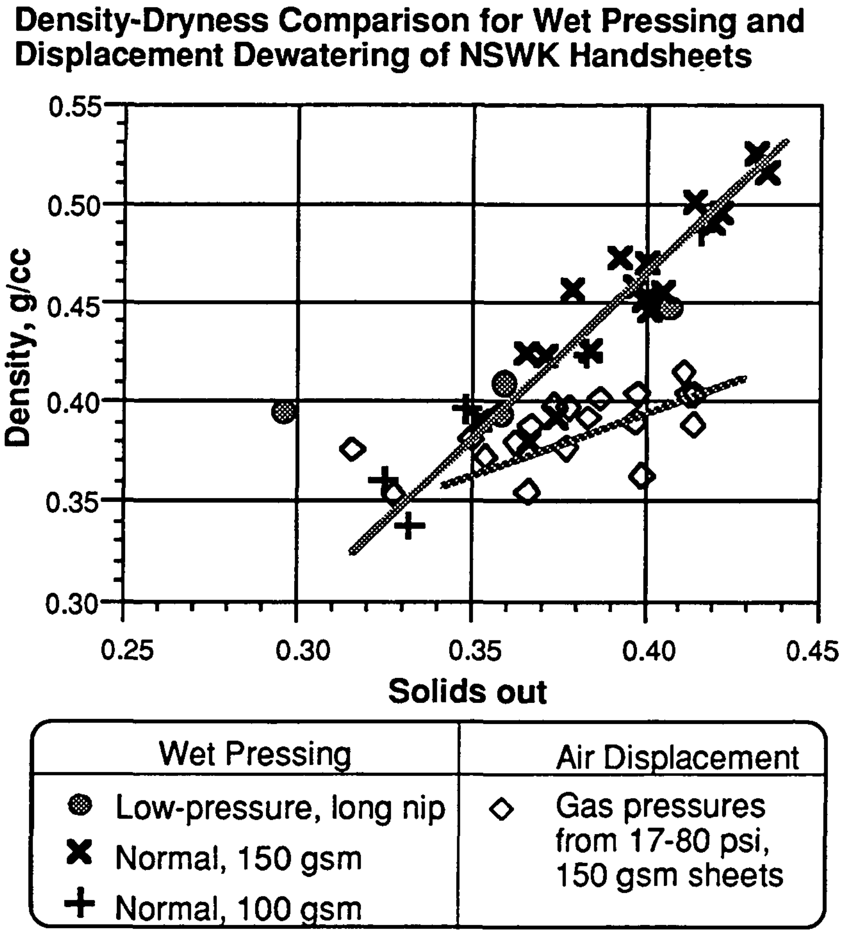


Figure 14. Density-dryness relationships for wet pressing and displacement dewatering in Northern softwood unbleached kraft handsheets. Solids in = 23-25%.

The density-dryness relationship for displacement dewatering appears decoupled from the wet pressing relationships, giving higher bulk for a given dryness level. The density-dryness relationships for low-pressure wet pressing and normal wet pressing (for both basis weights examined) appear similar, except for an unusually dense sheet from low-pressure wet pressing at 30% solids out. The latter data point may be due to a creep effect at low pressure: the pressure was probably insufficient to generate much water flow, but may have been enough to densify the sheet.

In an earlier unpublished presentation (39), an error in plotting the wet pressing results lead to the false conclusion that low-pressure wet pressing yielded higher sheet densities than normal wet pressing, and that displacement dewatering was not effective in maintaining bulk compared to wet pressing. Figure 14, containing the correctly plotted data, is consistent with other data sets from this study showing that displacement dewatering does succeed in maintaining bulk.

Similar runs were then conducted for 100 gsm NWSK linerboard sheets. Mechanical pressures ranged from 150 to 240 ms, and lower mechanical pressures were used, with peaks of 1.2-1.4 MPa (180-200 psi). Gas exposure times were still at 120 ms, with gas peak pressures lasting for 50-70 ms. In addition to air displacement, superheated steam was also used. The dewatering results for both air and steam displacement are shown in Figure 15, and density information is given in Figure 16. With such low mechanical pressure, low-pressure wet pressing alone raised the solids level from 0.25 to just 0.28. Air displacement was more effective, but the gains are not impressive. Steam dewatering again shows more promise, with over 44% solids possible. However, in this case steam displacement can increase the densification of the sheet, probably by thermally softening the sheet and decreasing its resistance to compression. Air displacement process gives better bulk than low-pressure or normal wet pressing (see the data in Figure 14 above)

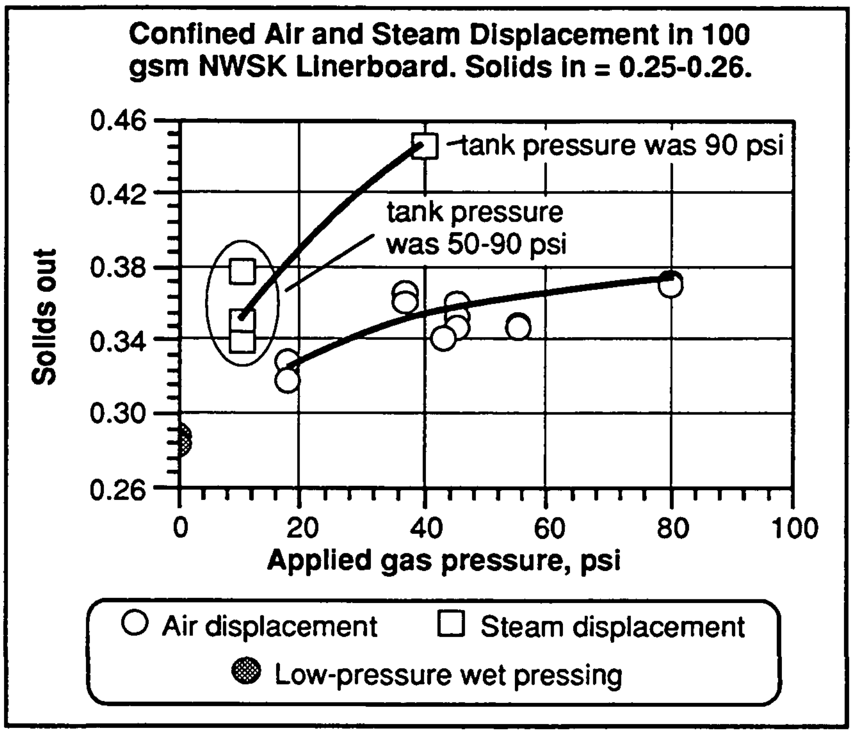


Figure 15. Steam and air displacement in 100 gsm NWSK sheets. Peak mechanical pressures were 1.2-1.4 MPa (180-200 psi).

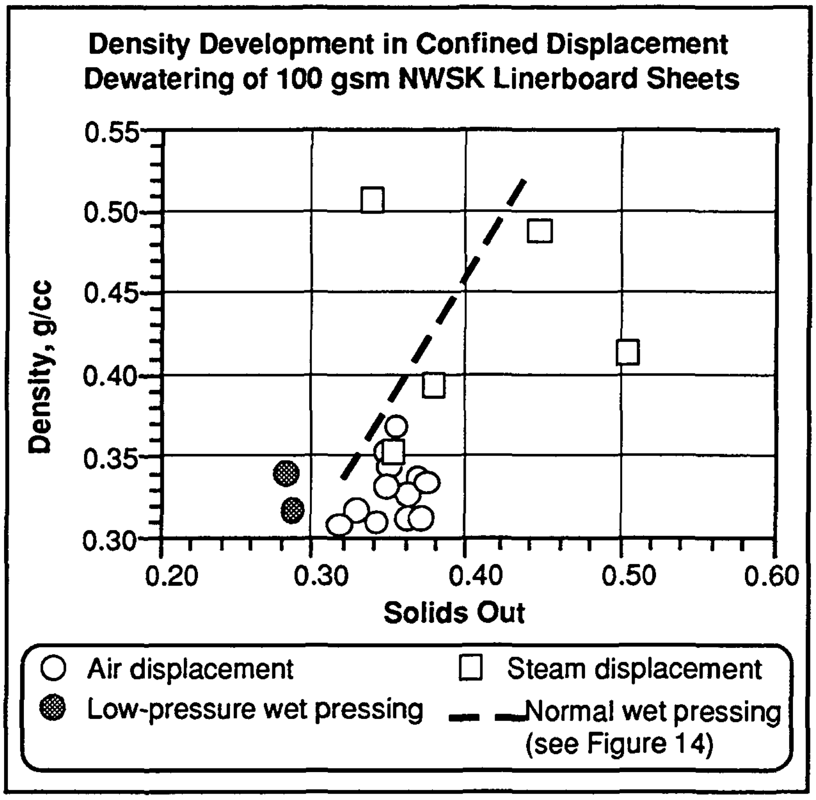


Figure 16. Density-dryness relationship in steam and air displacement dewatering of 100 gsm NWSK sheets.

To confirm the new density-dryness relationships for displacement dewatering (see Figures 14 and 16), further tests were run with a hardwood pulp. An unbleached kraft furnish from red oak was obtained with a CSF of 655. Handsheets were formed with 20-21% solids. Air displacement was done using nip residence times of 100-140 ms, peak mechanical pressures of 1.7 to 2.5 MPa, and gas pulses about 90 ms long. Gas tank pressures ranged from 0.3 to 0.5 MPa (50 to 70 psi). Displacement dewatering was done with the sheet between two felts instead of a felt and a fabric or wire mesh. Low-pressure wet pressing was done with the sheet between a solid surface and a felt, or between two felts with a solid surface above the upper felt. No obvious difference was seen in wet pressing results due to the pressing configuration. Density-dryness results for displacement dewatering and low-pressure wet pressing are shown in Figure 17 below. The results confirm the ability of displacement dewatering to decouple dryness and density from the trends given by wet pressing. The improvement in water removal is slight, however, and would have been better if higher gas pressures or lighter sheets had been used.

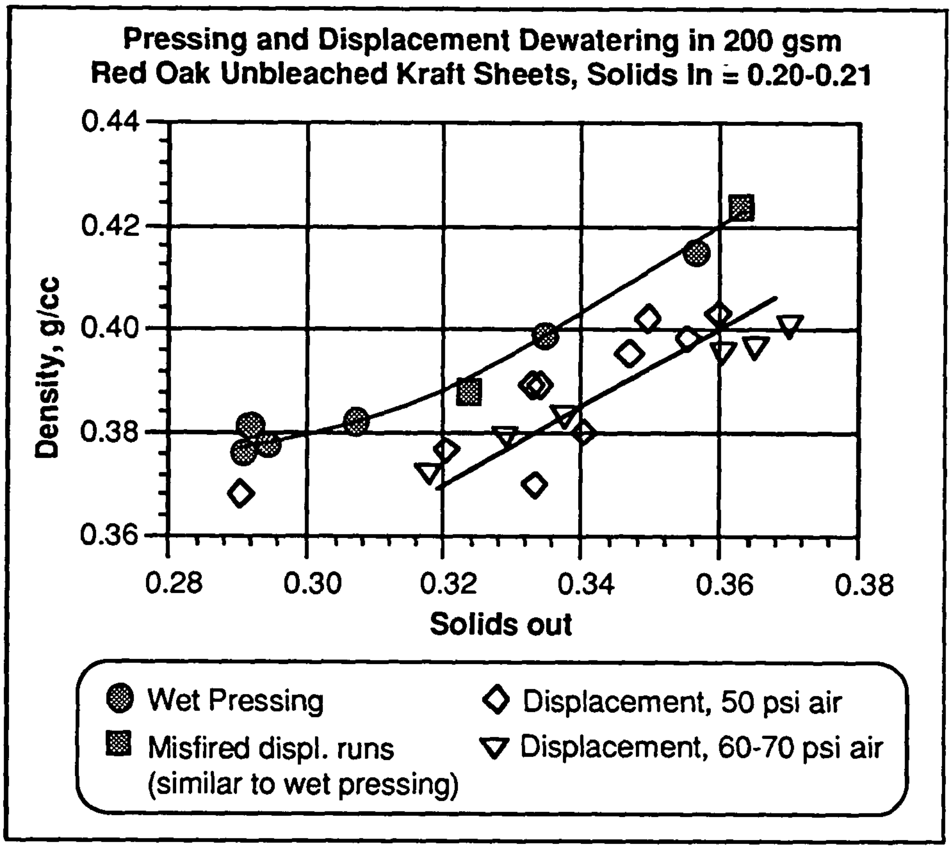


Figure 17. Density-dryness relationships for low-pressure wet pressing and displacement dewatering in unbleached red oak kraft sheets.

**Path-dependent Density-dryness Relationships: Further Pressing Work**

Several experiments were conducted to more thoroughly compare the density-dryness relationships obtained from normal and low-pressure wet pressing. Using a Southern softwood unbleached kraft pulp, handsheets at 23-25% initial solids were pressed using a wide range of press conditions. Nip residence times ranged from 15 to 1000 ms, and peak pressures ranged from 1.0 to 16.3 MPa. Long, low-pressure nips represent the pressing that occurs under displacement dewatering conditions, for displacement dewatering seeks to use low peak pressures to avoid densification but requires long gas exposure times (>50 ms) for effective water removal. In the wet pressing work reported here, no gas was applied, and pressing occurred between two solid platen surfaces. The results suggest that the density-dryness relationship is path dependent, as shown in Figures 18 and 19 below.

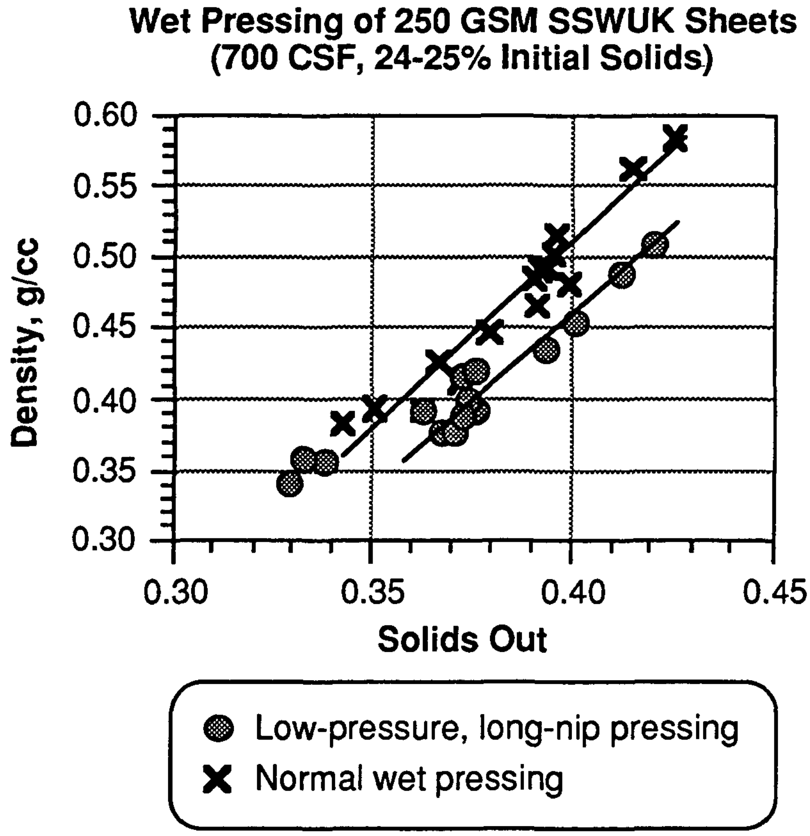


Figure 18. Wet pressing density-dryness relationship in linerboard handsheets. Low-pressure wet pressing has peak pressures < 3 MPa and residence times > 100 ms. "Normal" pressing data have peak pressures greater than 4.8 MPa and residence times less than 60 ms.

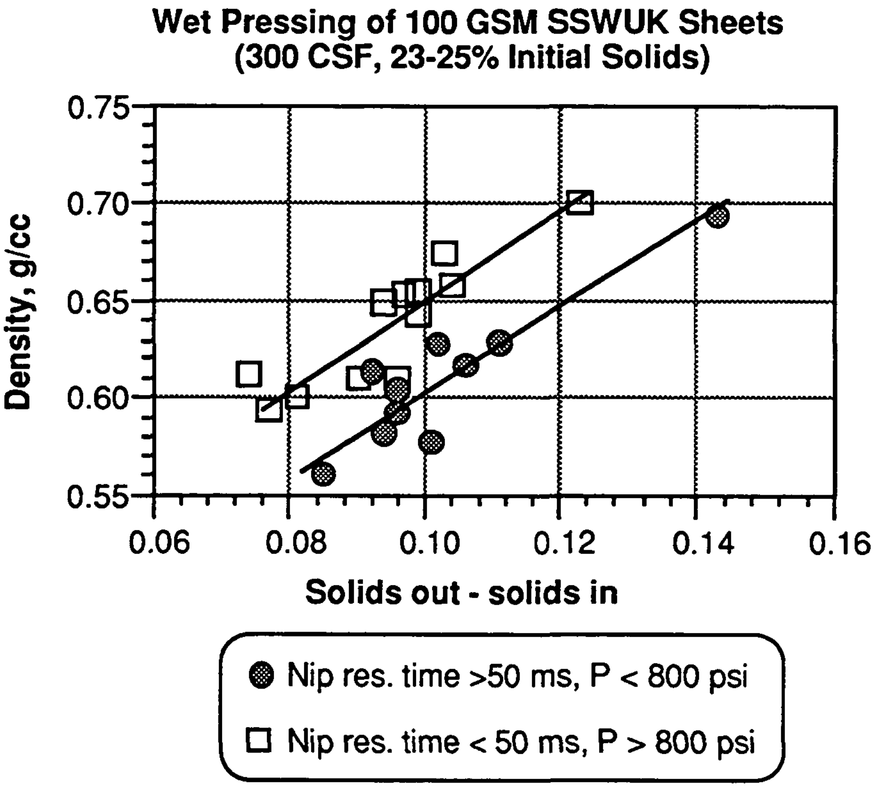


Figure 19. Wet pressing density-dryness relationship in linerboard handsheets showing less densification with long-nip pressing.

**Experimental Artifacts at Low Gas Pressures**

In the figures above, results from open surface pressing have not been included because they have little relevance to practical water removal. The low dryness levels achieved are an experimental artifact. A similar artifact occurs when displacement dewatering is done with gas at too low a pressure to overcome the adverse effect of using an open pressing surface. In that case, often observed with pressures below 25-30 psi (ca. 0.2 MPa), displacement dewatering gives worse results than low-pressure wet pressing with the same nip conditions. For example, Figure 20 shows the full air displacement data set from which Figure 13 was taken. Included here are low-gas pressure displacement data, which were discarded in Figure 13 for clarity (i.e., for simplicity, the discussion of low-pressure artifacts was postponed). As Figure 20 shows, over 30 psi (0.2 MPa) was required to overcome the adverse effect of an open upper platen. The "post-nip gas pulse" datum refers to a run in which the solenoid valve did not open until after paper had been pressed. This data point indicates the relative ineffectiveness of applying the gas phase when the sheet is not under a mechanical load.

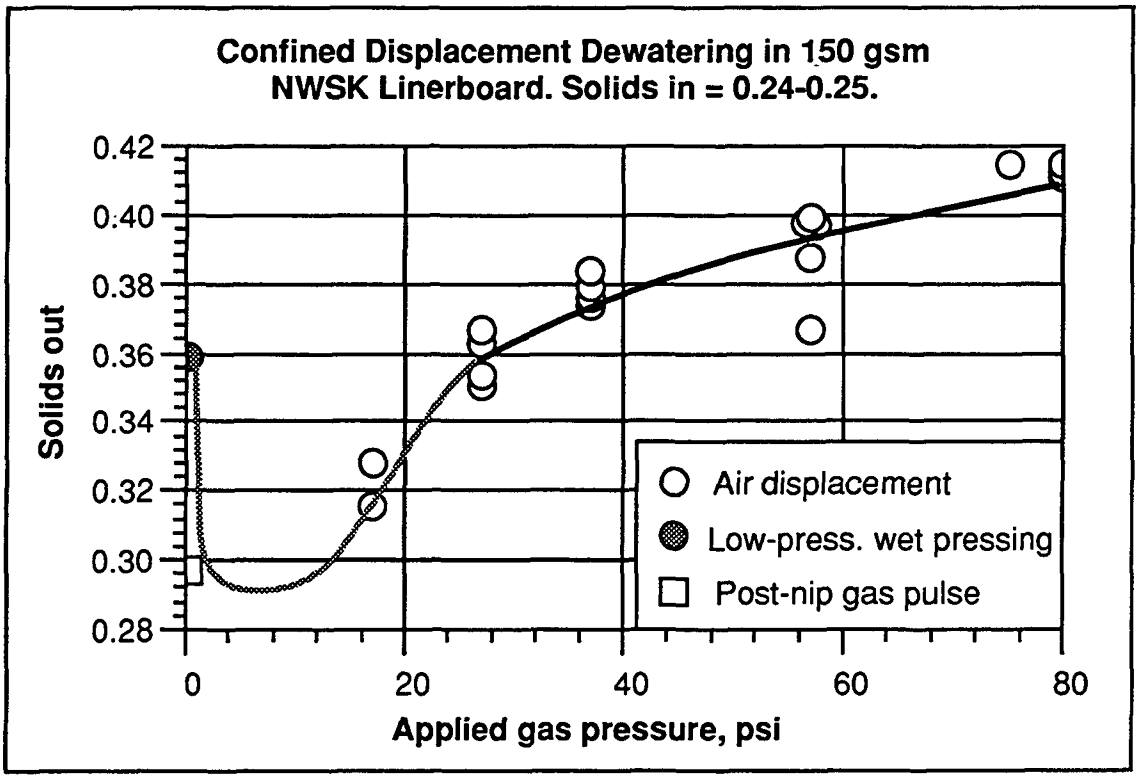


Figure 20. Confined air displacement in 150 gsm NWSK sheets.

Data for confined air displacement in blotter paper, previously shown in Figure 12, are again shown in Figure 21, but now with the full data set from that run. Displacement pressing at low gas pressure is worse than similar low-pressure wet pressing because of the lower hydraulic pressures generated under the open holes of the drilled bronze plate. Figure 21 also includes data for cases when the gas pulse came after the paper had been largely decompressed, but the seal between the upper and lower heads was still intact. These are shown at 0 psi since no gas was applied during the bulk of the mechanical pressure pulse. Such data again show the losses in dewatering when the sheet is not under sufficient mechanical pressure. Two data points are also shown from displacement runs where the solenoid valve failed to open, resulting in open surface wet pressing. The low dewatering (37% solids out) compared to regular wet pressing data (45% solids out) shows the adverse effect of pressing without a solid surface over the sheet.

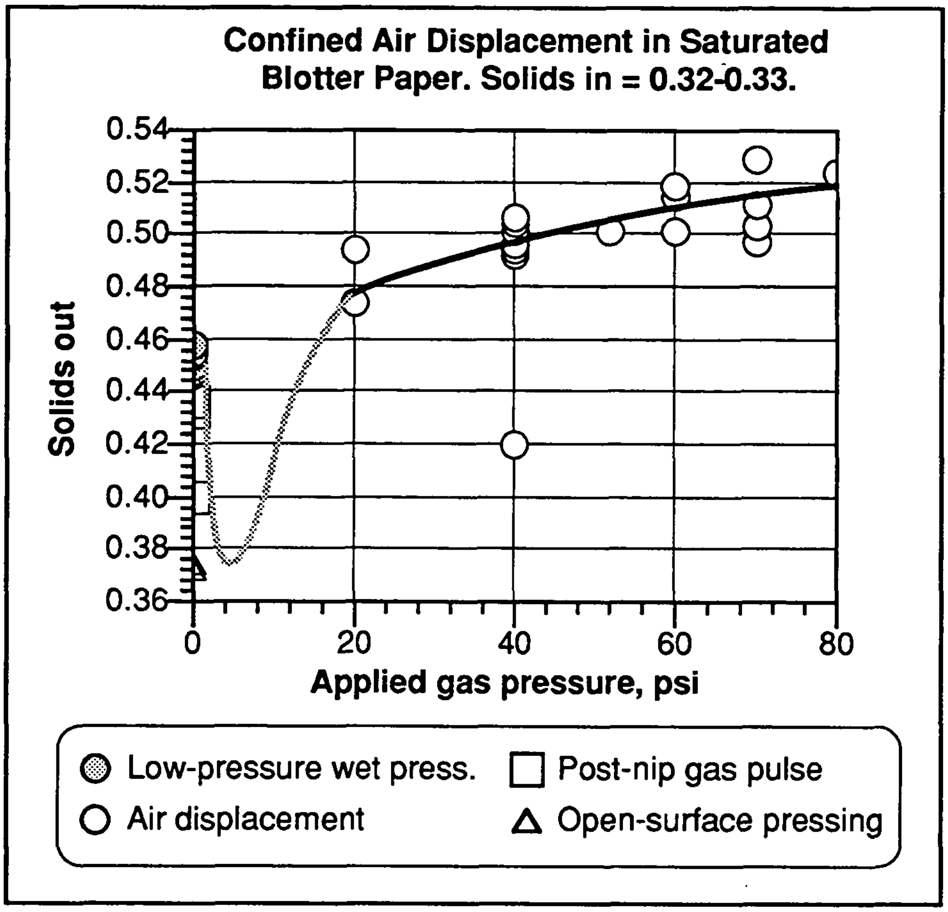


Figure 21. Full data set of air displacement results in saturated blotter paper (partially shown in Figure 12).

## DISCUSSION

### Improvements in Bulk

In evaluating the commercial potential of displacement dewatering, we must focus on the ability to give added control over paper properties, with bulk or sheet density being most critical. The degree of water removal is also important. Both can be discussed in terms of density-dryness results.

Based on simple theoretical considerations, improved control over bulk should be easily achieved and has been the primary motivation for this study. The potential to control bulk is best examined by comparing density-dryness data for displacement dewatering and wet pressing. Several pitfalls arise, however, in making this comparison. If displacement pressing is compared to "wet pressing" done in the same way but without any gas (i.e., open-surface wet pressing, as defined above), the results can be impressive. Much higher dryness levels are achieved with no significant loss in bulk. But this is not a proper comparison because of the adverse effect of wet pressing with an open, porous surface in contact with the sheet.

A more logical evaluation can be made by comparing displacement dewatering with wet pressing (no gas) done under the same press conditions, but now with a solid surface replacing the wire or mesh to generate a wet pressing event. While this is termed low-pressure wet pressing because of the low mechanical pressures that were applied, the long nip residence times used should also be kept in mind. Compared to low-pressure wet pressing, displacement dewatering gives improved water removal once a certain gas pressure threshold is reached (ca. 30 psi or 0.2 MPa for the conditions of this study). Higher bulk levels for a given solids content can usually be achieved, and the process thus appears to have promise. Compared to normal wet pressing, with shorter nips and higher peak pressures, displacement dewatering is also successful in maintaining bulk. Compared to low-pressure wet pressing, the density-dryness relationship for normal wet pressing is the same or may be shifted to higher densities, suggesting path-dependent consolidation. In any case, displacement dewatering appears capable of giving the papermaker increased control over paper properties relative to wet pressing.

**Inherent Inefficiency**

Water removal by displacement dewatering is good but not dramatic, with solids out often just a few percent higher than the corresponding low-pressure wet pressing process. The inherent inefficiency of viscous fingering probably limits water removal performance. In fact, the classical concept of viscous fingering during gas-liquid displacement in porous media may underpredict the problems faced in displacement dewatering. The theory of viscous fingering is based on the concept of a homogeneous porous medium, meaning that for the length scales of interest in the problem, the medium can be treated as a single substance, a smooth blend of solid and void volumes. In such a system a flat interface between two phases during displacement could exist and could propagate without change were it not for unfavorable viscosity ratios. But in a thin structure like paper, where the solid elements are not tremendously smaller than the sheet thickness, the concept of homogeneity becomes inapplicable. Instead, we must realize that there will be some large, easily emptied pores and many small or blocked pores through which displacement cannot occur. As a result, the displacement process considered here is bound to be less efficient than theory would predict. Blow-through may always occur under practical conditions. [See Brundrett and Baines (40) for a discussion of the flow of air through uncompressed but wet sheets.] Water removal in "displacement dewatering" is thus likely to be a combination of displacement, entrainment, evaporative drying, and rewet resistance. The latter mechanism has been discussed in the context of impulse drying (20) and is likely to apply here: gas pressures existing in the sheet during nip expansion can continue driving water into the felt, resisting back flows from the felt into the sheet.

**The Drawback of Long Nip Times**

One of the main difficulties with the displacement dewatering concept is the relatively long time required for displacement to occur in a sheet. Compression is needed to saturate the sheet and bring water into the extrafiber pores, but this decreases permeability and slows displacement. Heating the sheet will reduce viscosity and perhaps improve displacement, but thermal softening will also increase densification and thus lower permeability. Minimum gas exposure times for effective water removal in a typical linerboard sheet are on the order of 50 ms or more. Compared to the current maximum dwell time of 20 ms in a long nip press, 50 ms or more seems problematic.

Further study is required to examine the mechanical limitations of displacement dewatering with respect to a paper machine. Possible solutions will be explored in the future. However, there are a number of commercial processes which already require fairly long, low pressure nips for production of specialty products or piece goods. A retrofit for displacement dewatering may be easily achieved in some cases.

## CONCLUSIONS

A new water removal strategy, displacement dewatering, has been tested. Results show increased water removal without significantly increased bulk is possible. Long gas exposure times may be required, however.

The next phase of this study requires development of a strategy to test displacement dewatering under more practical industrial conditions. A major task will be determining the proper combinations of process conditions for optimum performance (minimizing the required nip residence time, for example). There are several possibilities for retrofitting existing paper machines with displacement dewatering technology, but many engineering challenges must be faced before a true pilot scale device can be built and tested.

## ACKNOWLEDGMENTS

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## LITERATURE CITED

1. Holden, G. R., "Apparatus for Dewatering of Fibrous Webs in Papermaking and Similar Machines," U. S. Patent 3,284,285, (Nov. 8, 1966).

2. Kawka, W., "Theoretical and Experimental Analysis of the Blow-Through Process of Fibrous Web Dewatering" (transl.), Przeglad Papier., 39(11/12): 403-407 (1983).

3. Kawka, W. and Ingielewicz, H., "A New Technology for Producing Porous Papers Using Through Dryers" (transl.), Przeglad Papier., 30(1): 10-18 (Jan. 1974).

4. Kawka, W. Ingielewicz, H., and Marek, I., "Study of Equipment for Intense Dewatering and Drying of Porous Paper Products," Przeglad Papier., 34(3): 82-87 (March 1978).

5. Kawka, W. and Szwarcsztajn, E., "Some Results of Investigation on the Equipment for Intensive Dewatering and Drying of Porous Papers," EUCEPA-79, Web Formation and Consolidation, 18th International Conference, London, May 21-24, 1979.

6. Kawka, W. and Ingielewicz, H., "Dewatering and Drying of the Paper Web on the Machine by the Method of Air Blowing," Przeglad Papier., 28(11): 381-387 (1972).

7. Kawka, W. "Optimum Consolidation of Absorbent Fibrous Webs on Paper Machines with Air Blow-Through Presses" (transl.), Przeglad Papier., 41(5): 163-169 (May 1985).

8. Kawka, W. "Principles of Paper Dewatering by the Air Blow-Through Method" (transl.), Przeglad Papier., 34(2): 53-58 (1978).

9. Kawka, W. and Szwarcsztajn, E., EUCEPA-79 International Conference, London, May 21-24, 1979.

10. Walser, R. and Swenson, R. S., "Air Through-Drying of Paper," Tappi J., 51(4): 184-190 (1968).

11. Holik, H., "Zur Durchstromtrocknung von Papier," Das Papier, 26(4): 153-161 (1972).

12. Villalobos, J. A., "Paper Machine Hoods, Pocket Ventilation, Heat Recovery and Thru-dryers," TAPPI 1988 Practical Aspects of Pressing and Drying.

13. Bryand, E. T., "Energy-conserving Drying Methods," Paper Tech. and Ind., 16(1): 24-29 (1975).

14. Randall, K. R., "Using High-velocity Impingement Air to Improve Through Drying Performance on Semi-Permeable Webs," Drying 84. Ed. A. S. Mujumdar, Wash., D. C., Hemisphere Publ. Corp. (1984).

15. Burgess, B. W. and Chapman, S. M., "Turbulent Drying Process," U.S. Patent 3,418,723 (1968).

16. Burgess, B. W., Koller, W., and Pye, E., "The Papridryer Process Part II - Mill Trials," Pulp and Paper Mag. Canada, 73(11): 73-81 (1972).

17. Sprague, C. H., "New Mechanisms in Web Consolidation," Pira Paper and Board Division International Conference, Brighton, Sussex, England (May 19-23, 1986).

18. Lavery, H. P., "New Mechanisms for Water Removal From Paper Through Impulse Drying," AIChE Summer Meeting, Minneapolis, Minnesota, Aug. 16-20, 1987. Also printed as IPC Technical Paper Series #251, The Institute of Paper Chemistry, Appleton, WI, July, 1987.

19. Zavaglia, J. C., and Lindsay, J. D., "Flash X-ray Visualization of Multiphase Flow During Impulse Drying," Tappi J., 72(9): 79-85 (Sept. 1989).

20. Lindsay, J. D., "The Physics of Impulse Drying: New Insights from Numerical Modeling," The Ninth Fundamental Research Symposium, Cambridge, England, Sept. 16-22, 1989.

21. Gottwald, B. C., Halsey, B. S., Williams, R. C., and Haigh, J. M., "Continuous Process of Drying Uncoated Fibrous Webs," U.S. Patent 3,354,035 (Nov. 21, 1967).

22. Clemens, M. L. and Morton, W. J., "Method and Apparatus for Continuously Expelling an Atomizing Stream of Water from a Moving Fibrous Web," U.S. Patent 4,157,938 (June 12, 1979).

23. Sprague, C. H., "New Concepts in Wet Pressing," Final report prepared for the US DOE by the Institute of Paper Chemistry, Appleton, Wisconsin (now IPST, Atlanta), Report No. DOE/CE/40685-T1, U.S. DOE, Office of Industrial Programs, Conservation and Renewable Energy Division, Washington, D.C., March 1986.

24. Lindström, T., "The Concept and Measurement of Fiber Swelling," Paper - Structure and Properties, ed. J. A. Bristow and P. Kolseth, pp. 75-97, Marcel Dekker, Inc., New York, NY, 1986.

25. Carlsson, G., Lindström, T., and Scöremark, C., "Expression of Water from Cellulosic Fibres Under Compressive Loading," Fibre-Water Interactions in Papermaking, Transactions of the Symposium at Oxford, Sept. 1977, British Paper and Board Ind. Fed., London, 1977.

26. Stone, J. E., and Scallan, A. M., "The Effect of Component Removal Upon the Porous Structure of the Cell Wall of Wood. Part III. A Comparison Between the Sulphite and Kraft Processes," Pulp and Paper Canada, 69(12): 69/T288 (June 21, 1968).

27. Carroll, M., and Mason, S. G., "The Measurement of Fiber Swelling by the Liquid Permeability Method," Can. J. Tech., 30: 321 (1950).

28. Mason, S. G., "The Specific Surface of Fibers - Its Measurement and Application," Tappi J., 33(8): 403 (Aug. 1950).

29. Carlsson, G., "Some Fundamental Aspects of the Wet Pressing of Paper," Ph.D. Dissertation, Dept. of Paper Technology, The Royal Institute of Technology, Stockholm, Sweden, 1983.

30. Bear, J., "Dynamics of Fluids in Porous Media," American Elsevier, New York, NY, 1972, pp. 439-440.

31. Chuoke, R. L., van Meurs, P., and van der Poel, C., "The Instability of Slow, Immiscible, Viscous Liquid-Liquid Displacements in Permeable Media," Petroleum Transactions AIME, 216: 188-194 (1959).

32. Homsy, G. M., "Viscous Fingering in Porous Media," Ann. Rev. Fluid Mechanics, 19: 271-311 (1987).

33. Lenormand, R., Touboul, E., and Zarcone, C., "Numerical Models and Experiments on Immiscible Displacements in Porous Media," J. Fluid. Mech., 189: 165-187 (1988).

34. Hahn, P. S., Ramamohan, T. R. and Slattery, J. C., "Mobility Control in the Displacement of Residual Oil by an Unstable Foam," AIChE J., 31(6):1029-1035 (1985).

35. Skelton, J., "Foam Assisted Dewatering - A New Technology Emerges," Paper Tech. and Ind., 28: 435-436 (1987).

36. Lindsay, J. D., "The Anisotropic Permeability of Paper," Tappi J., 73(5): 223-229 (May 1990).

37. Lindsay, J. D. and Wallin, J. R., "Characterization of In-Plane Flow in Paper," AIChE Annual Meeting, Chicago, Illinois, Nov. 11-16, 1990.

38. Miller, C. A., "Stability of Moving Surfaces in Fluid Systems with Heat and Mass Transport," AIChE J., 19:909-915 (1973).

39. Lindsay, J. D., "Experimental Evaluation of Displacement Dewatering," AIChE Annual Meeting, Chicago, Nov. 1990.

40. Brundrett, E. and Baines, W. D., "The Flow of Air Through Wet Paper," Tappi. J., 49(3): 97-101 (1966).